THE ROLE OF ALLUVIAL FANS IN THE MOUNTAIN FLUVIAL SYSTEMS OF SOUTHEAST SPAIN: IMPLICATIONS OF CLIMATIC CHANGE

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ABSTRACT

The mountain fluvial systems of southeast Spain involve sediment supply from steep mountain slopes into headwater channels. Alluvial fans often occur where these headwater channels emerge from the mountain areas, and may influence the connectivity of the sediment transport system from the mountain source areas to the main lowland drainages. Critical in this role is whether the alluvial fans are aggrading or dissecting, and whether there is a break or continuity in the channel through the fan environment. Previous work has identified some of the factors influencing the behaviour of the alluvial fans in southeast Spain. This paper deals with the mountain front alluvial fans in the semi-arid areas of Murcia and Almeria provinces. It attempts, by mapping the location of alluvial fans, then their classification into aggrading or dissecting fans, to identify the extent to which the mountain fluvial systems are buffered by aggrading alluvial fans or exhibit channel continuity through the mountain front environment. It further considers the implications of climatically induced changes between aggradational and dissectional behaviour on alluvial fans.

KEY WORDS climate change; alluvial fans; southeast Spain

INTRODUCTION

Alluvial fans are important zones within dry-region fluvial systems: they occur between mountain sediment source areas and lowland main drainages, and their erosional or sedimentational behaviour influences the connectivity of the fluvial system as a whole (Harvey, 1989). Aggrading alluvial fans may act as a buffer within the system, trapping and storing coarse sediment supplied by the mountain catchment, thus isolating the lowland drainage from major sources of sediment supply. However, if alluvial fans become trenched, continuity may be established throughout the system, linking mountain sediment source areas with lowland main drainages. Alluvial fans may therefore control sediment transport within the system but they themselves are controlled by the dynamics of the system.

Quaternary alluvial fans occur throughout southeast Spain at the margins of mountain ranges of the Betic system. Some of these have been studied previously in work dealing with their sedimentology, stratigraphy and morphological development (Harvey, 1984a, b, 1987a, 1988). That work focused on the relationships between fan aggradation and dissection but so far has only touched on spatial characteristics (Harvey, 1984b, 1987b, 1990). This paper deals specifically with locational and spatial characteristics, attempts to be comprehensive rather than selective, and considers the significance of aggradational and dissectional regimes in the context of potential climatic change. However, before discussing the distribution of the fans in southeast Spain it is necessary to review the previous work on their aggradation and dissectional behaviour.

FAN AGGRADATION AND DISSECTION

Many of the alluvial fans in southeast Spain have morphologies similar to those described in the standard

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Figure 1. Characteristic aggrading alluvial fan morphology, near Tabernas, Almeria

literature (e.g. Schumm, 1977; Bull, 1977), with proximal areas dissected by a fan-head trench, convergence of fan surface and channel to an intersection point in mid-fan, and aggradation in distal areas (Figure 1). Others show through-fan trenching, with dissection in mid-fan and distal areas (Figure 2), and confined channel continuity through the fan. This distinction is critical in determining contemporary patterns of erosion and deposition within dry-region fluvial systems as a whole.

Figure 2. Mid-fan trenching by headcut development, Torre fans, near Mazarron, Murcia

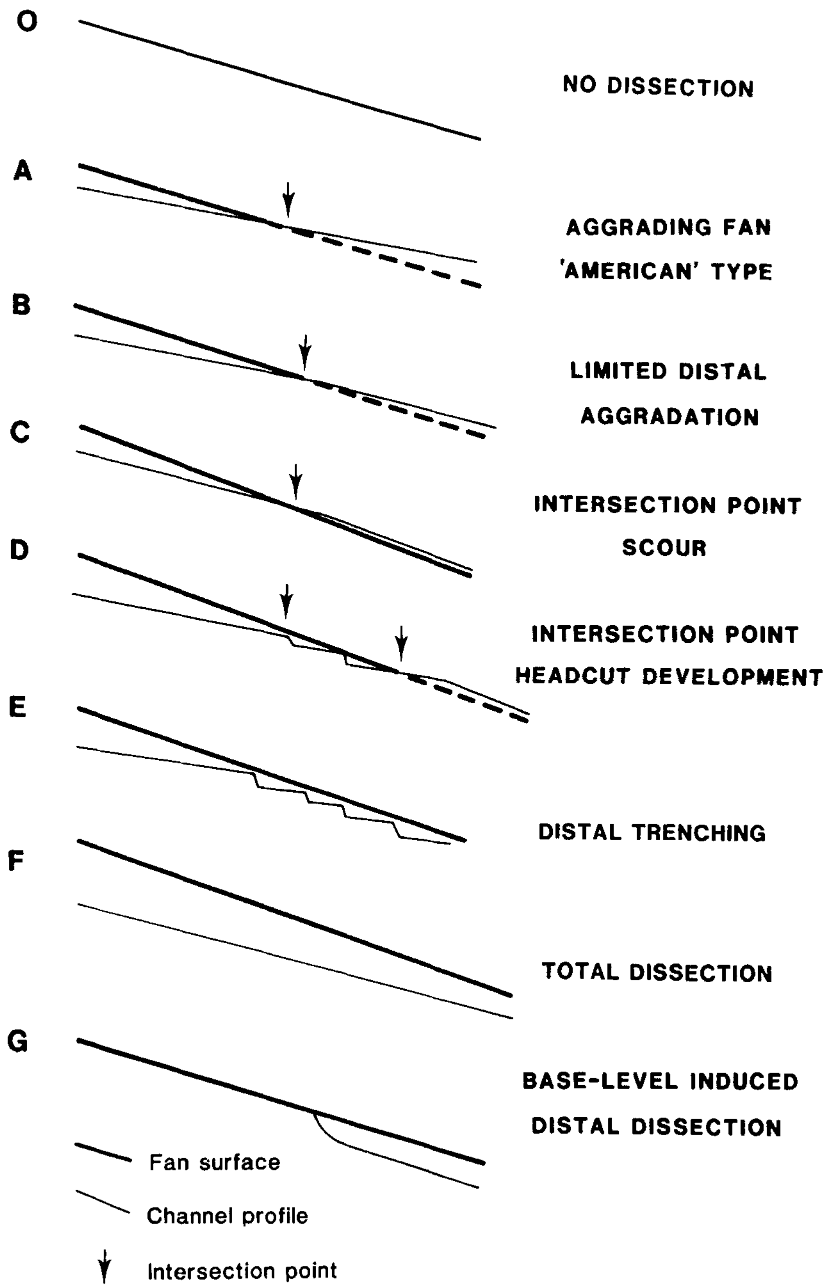

Figure 3. Schematic model of fan profile types (modified after Harvey, 1987b, 1988)

Fan-head trenches have received much attention in the literature. Schumm *et al.* (1987) list 16 possible causes of trenching, but these can be grouped into three: intrinsic causes, related to random process variations or random oscillation between erosion and deposition in the fan-head area; extrinsic causes, related to changes in water and/or sediment supply to the fan environment; and ageing-related causes, first identified by Echis (1928), and associated with fan-toe progradation. Mid-fan and through-fan trenching, on the other hand, have received much less attention, primarily on calcrete-crusted fans in southeast Spain (Harvey 1978, 1984b, 1987a, 1988; Segura Beltran, 1990).

Schematic fan profile types, distinguishing distally aggrading from distally trenched fans, are shown in

Table I. Characteristics of major alluvial fan groups in southeast Spain (for locations see Figure 4)

Fan group	Description and source area	Geology[1]	Quaternary tectonics	Regional dissection	Dominant fan size[2]	Dom. facies[3]	Quat. seq.[4]	Crusted surfaces[5]	Profile types[6]	Dissection styles[7]	Potential fan disssection[8]
1 Tabernas (3 subgroups)	(a) Large coalescent fans, S de los Filabres	B M	Passive	Between Rio Alias & Andarax	1–4	F	1	O	B	F D	(B)
	(b) Small fans on N of S. de Marchante	M	Minor fault	Rio Andarax	2	DF	2	A	C	F S D	I (B) (M)
	(c) Isolated, dissected fans S. de Alhamilla (N)	B T	Alhamilla mt.-front faults	Rio Andarax	2	DF	3	X	FG	T	B
2 Nijar (3 subgroups)	(a) Fans below dissected pediments S. de Alhamilla(S)	B T	Alhamilla faults	Almeria Basin	2–3	F	2	O	O	A	—
	(b) Large fans S. de Alhamilla (S)	B T	Alhamilla uplift	Central Almeria basin	4	DMF	2	A	BD	F (M) D	(M)
	(c) Small fans on La Serrata	V	Carboneras faults	Central Almeria basin	2	M	2	A	B	F D	—
3 C. de Gata	Small fans S. de Cabo de Gata	V	Passive	Almeria basin (coastal zone)	2	M	1	O	B D	A (F) (M)	(M)
4 Vera Basin (3 subgroups)	(a) Small fans, W of Vera Basin	T	Passive	Vera Basin centre	1	D	1	X	C D	(F) S D	(M)
	(b) Small fans, Almanzora Valley	T	Almagro uplift	Rio Almanzora	2	M	3	X	F G	T	B
	(c) Dissected fans, S. de Almagro	T T	Almagro uplift	Rio Almanzora	2	M	3	X	F	T	B
5 S. de Enmedio	Large coalescent fans, S. de Enmedio S. de Estancias	T B M	S end of Guadalentin fault system	Between Rios Fuadalentin & Almanzora	2–4	F	1	A	A B	A F D	—
6 Guadalentin Valley (Pto Lumbreras -Librilla)	Large and small fans, Sierras W of Guadalentin trough	T B M	Guadalentin fault system	R.Guadalentin	1–4	M F	1	O	A B	(A) (F) D	—
7 S. de Almenara (2 subgroups)	(a) Mt front fans, S. de Almenara (W)	B	Mt front faults N Extension of Polomares fault	Between Rios Guadalentin and Almanzora	2–3	M F	2	A	B	(F) D	I

Table 1 continued

	(b) Interior fan system, S. de Almenara (S)	B	Local faults and passive zones	Coastal drainage	3	F	2	A	B	F D	—
8 Mazarron (2 subgroups)	(a) Small dissected fans S. des las Moserras	B T	Almenara/ Mazarron uplift	Mazarron system	1–2	M F	2	X	B D F	F S	(M)
	(b) Torre fans, S de Alto and S de la Mulla (S)	B T	Mazarron/ Cartagena uplift	Coastal systems	2–3	D M F	2	X	D E	F M	M
9 Carrascoy (2 subgroups)	(a) Mt front fans Carrascoy (N)	T	Carrascoy faults	Guadalentin system	1–3	D M F	4	X	C D	F S (M) D	I
	(b) Interior and southern Carrascoy (C & S)	T	Passive	Campo de Cartagena	2–4	M F	4	X	D E	F M T	M

1 Geology: M, Miocene sedimentary rocks; V, Miocene volcanic rocks; T, basement (Triassic) sedimentary and low grade metamorphic rocks; B, basement (Palaeozoic) medium and higher grade metamorphic rocks.
2 Dominant fan sizes (and size range): 1, $< 0{\cdot}5\,km^2$; 2, $0{\cdot}5$–$2\,km^2$; 3, 2–$5\,km^2$; 4, $> 5\,km^2$.
3 Dominant facies exposed in fan sections: D, debris flow; M, mixed (intermediate); F, fluvial.
4 Quaternary sequences: 1, aggradation dominant, recent dissection only, no cut/fill phases evident: 2, limited dissection, one inset terrace; 3, dissection dominant, one inset terrace; 4, complex sequence - major dissection, two or more inset terraces.
5 Crusted surfaces: O, little or none; A, limited to apex areas; X, extensive.
6 Profile type (see Figure 3).
7 Dissection styles (brackets indicate localized features only): A, dominantly aggradational; F, fan-head trench; M, mid-fan trench; S, mid-fan scour; T, through-fan trench; D, distal aggradation.
8 Potential fan dissection (brackets indicate secondary potential)): M, in mid-fan; I, by interfan channel; B, by base-level-induced dissection.

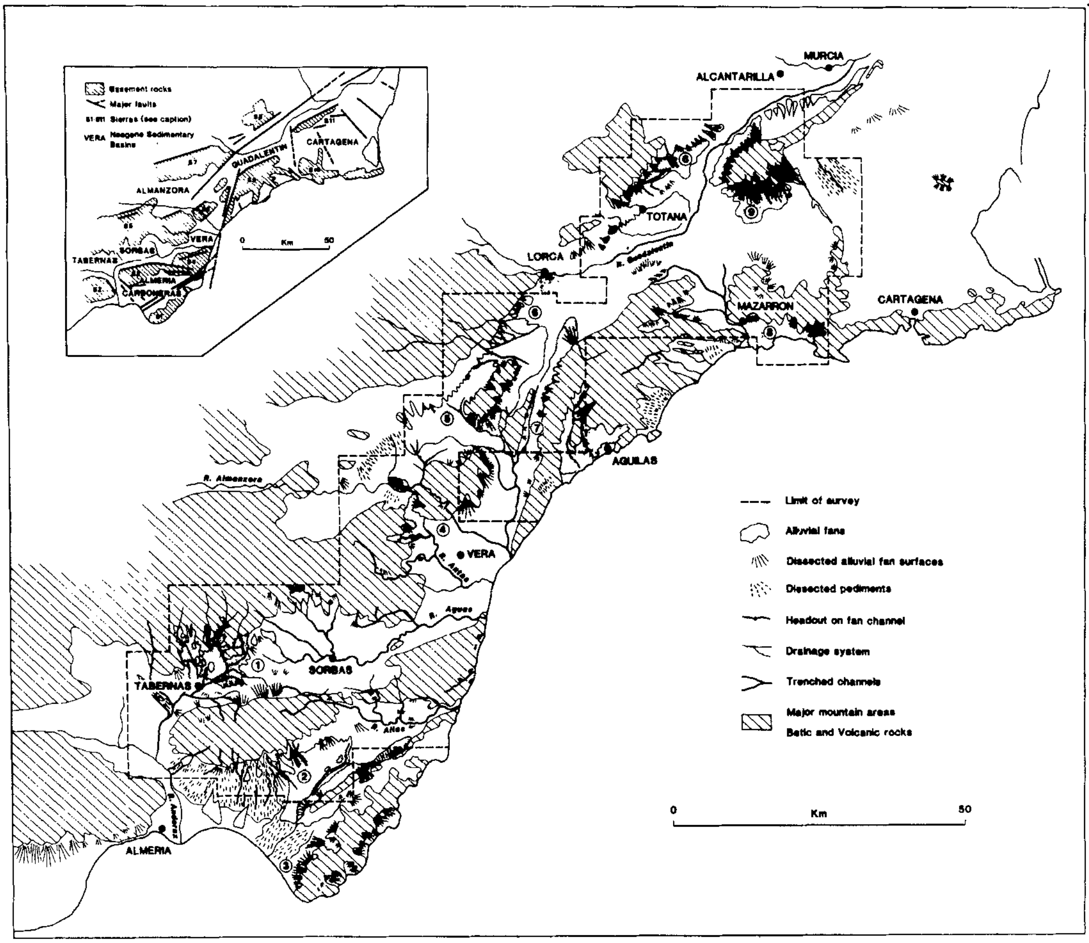

Figure 4. Distribution of Quaternary alluvial fans in southeast Spain. Numbers 1–9 on the main map refer to alluvial fan groups (see text and Table I). Inset shows major tectonic units. Mountain ranges S1–11 are as follows: S1, Sierra de Cabo de Gata (Miocene Volcanic rocks). The remainder are all of Palaeozoic to Triassic metamorphic and Triassic sedimentary rocks of the Betic system: S2, Sierra de Gador; S3, Sierra de Alhamilla; S4, Sierra Cabrera; S5, Sierra de los Filabres; S6, Sierra de Almagro; S7, Sierra de las Estancias; S8, Sierra Espuna; S9, Sierra de Almenara; S10, Mazarron-Cartagena Sierras; S11, Sierra de Carrascoy

Figure 3. Type O shows no dissection. Types A B and C show fanhead trenching only; type A has channel-slope continuity through the intersection point, as described for many American fans, although many of these in reality appear to be of type B, with an increase in channel slope at the intersection point (Harvey 1987a, 1990). Types D and E show intersection-point headcut development and distal trenching, controlled by stream power/sediment transport relationships in mid-fan. Type G shows base-level-induced distal dissection. The ultimate end product of both types E and G may be the through-trench shown as type F.

Harvey (1987b) has suggested that distal trenching (fan types D and E) instead of distal aggradation (fan types A and B) occurs under conditions of reduced sediment supply but relatively high stream power. These conditions are met (i) where there is a major discrepancy between fan slope and channel slope at the intersection point, accentuated if fan surface aggradation took place by debris flow or coarse sediment sheetflood deposition, rather than by within-channel fluvial deposition, and (ii) where channel widths are relatively small, enhancing unit stream power, and do not rapidly increase at the intersection point, thus counteracting any increase in stream power which may result from the steepening of slope common at this location. These latter conditions are favoured by calcrete-crusted fan surfaces because of their influence on channel confinement (Van Arsdale, 1982; Harvey, 1987b).

The Spanish alluvial fans show a complex Quaternary history (Harvey, 1977, 1984b) with early periods dominated by aggradation, followed by the formation of calcrete crusts on stable fan surfaces. Later periods were dominated by dissection during which time fan-head trenches and through-fan trenches developed. Both earlier dominantly aggradational and later dominantly dissectional phases were marked by episodic alternations between erosion and deposition, generally speaking with more complexity in the northern, more humid areas, and less in the more arid south. Furthermore, there are both spatial and temporal variations in sedimentology (Harvey, 1984a, b), with debris flow as opposed to fluvial deposits more common earlier in the sequences and from smaller catchment areas, especially on sedimentary and low-grade metamorphic rocks, also occurring more commonly in the north than in the south of the area. Harvey (1990) has attributed these trends and differences firstly to an 'ageing' process reflecting a long-term diminution in sediment availability, which itself may be a protracted response to early Quaternary tectonics, and expressed by progressive trends from debris flow, to fluviatile deposition, to dissection. Secondly, and superimposed on this trend, are alternating periods of high and low sediment supply, presumably in response to Quaternary climatic fluctuations. Thirdly, spatial variations both at a regional scale, for instance the later onset of dissection in the south, and at a local scale, reflect spatially variable intrinsic causes as well as climatic factors, geology, topography and, in the Holocene, human activity.

METHODOLOGY

This paper represents an attempt to map all the mountain-front alluvial fans in part of southeast Spain between Murcia and Almeria (Figure 4). The limits of the survey were determined by the availability of air photographs (USAF 1956 series, scale *c* 1:32 000) in the University of Liverpool; however, the mapping has been extended beyond the boundaries of the air photo cover where fans have been mapped in the field. Within the whole area, alluvial fans have been mapped onto basemaps at a scale of 1:50 000. Using evidence from the air photos, together with prior field-based knowledge, aggrading and dissected fan surfaces have been differentiated and fans differentiated from early Quaternary pediment surfaces mantled by thin pediment veneers. Trenched drainage and trenched fan channels have been identified and fan channels with mid-fan headcuts (profile types D and E, Figure 3) have also been located. The mapped data are shown at a much reduced scale in Figure 4. In addition, data related to source areas and fan properties have been tabulated and summarized in Table I.

RESULTS

Figure 4 shows the distribution of alluvial fans within the study area. In a broad sense their locations relate to Neogene tectonism, which created the overall patterns of relief. The tectonics are dominated by a system of major strike-slip and reverse faults (Bousquet, 1977), creating a basin-and-range type of topography. Tectonic activity has continued into the Quaternary with movement along many of the faults (Dumas *et al.*, 1978) and with large-scale regional uplift (Harvey, 1987b). Some mountain fronts are directly associated with major faults but others are passive margins. Alluvial fans occur on both types of mountain front, on the passive margins often burying older pediment surfaces. Despite Quaternary tectonism, few alluvial fans appear to be directly affected by tectonic activity though some are faulted locally by both normal and reverse faults on a small scale (Harvey, 1988) and by strike-slip lateral movement (Harvey, 1990).

In more detail, fan location reflects the interaction of several factors; those related to source-area characteristics are summarized for each fan group in Table I. Intermediate-sized mountain source areas appear to be more important than very small catchments, which produce only small fans, or large river systems, few of which, with the exception of the Guadalentin at Lorca, show fan deposition where they enter a (usually now dissected) sedimentary basin. This may be the reason for the contrast between the Tabernas basin (Area 1, Figure 4), with major fans fed by a range of intermediate-size catchments, and the Vera basin, which has few and is fed by two large dissecting rivers and otherwise only very small mountain streams. Another important factor is the effectiveness of aggressive tectonically induced dissection in preventing fan accumulation at mountain fronts. Not all mountain fronts show alluvial fans, especially where there is a major dissecting river

in close proximity, for example, both north and south of the Sierra Cabrera (Figure 4) dissection by the Rios Aguas and Alias respectively has prevented fan formation. In fact many of the major fan zones occur in watershed positions between the major dissected drainage systems, e.g. Tabernas fans, zone 1, lie at the head of the Andaraz system, near the Aguas watershed; Nijar fans, zone 2, lie between the Almeria and the Alias system; both extensive zones 5 and 7 lie between Almanzora and Guadalentin drainages; and zone 9b (Carrascoy S) lies at the head of the Campo de Cartagena.

Also summarized in Table I are morphological characteristics of each major group of fans. Drainage area size, relief and geology have already been shown to influence fan sedimentology (Harvey 1984a) and in turn the sequence of morphological development (Harvey 1984b). The modern erosional and depositional behaviour is best summarized by profile type (Table I). Distally aggrading profiles (types O, A, B; Figure 3) are common, especially on large fluvially dominated fans in areas fed by metamorphic rocks. They are common in zones 1a, 2, 3 and 5–7 (Table I, see Figure 4 for location), and often show only simple Quaternary sequences and only limited surface crusting. Profiles with mid-fan headcut development and trenching occur in fan zones 2b, 3, 4a and 9b, mostly on intermediate-sized and smaller fans, often with either mixed or debris flow sediments, more complex Quaternary sequences and extensive well developed surface crusts. The intermediate (type C) fans might be regarded as near a trenching threshold and occur as isolated examples within zones 1b, 4a and 9a. Only on type G profiles, and possibly some examples of type F, can trenching be related to tectonically-induced distal dissection. Examples occur near Tabernas in zone 1c and along the Almanzora valley in zone 4b.

IMPLICATIONS

It is difficult to predict the effects of climatic change on the alluvial fans of southeast Spain, partly because, as in other dry-region fluvial systems (Baker, 1977), erosion and deposition occur only in response to extreme events (Harvey, 1984c). Such events are outside the usual range of climatic change models. Furthermore, behavioural changes within the alluvial fan systems involve trenching thresholds, governed by the threshold of critical stream power (Bull, 1979), relating aggradational or dissectional behaviour to sediment supply and unit stream power. Clearly, some fans today are aggrading while others are undergoing dissection. Nearness to threshold conditions and the sensitivity to environmental change (Brunsden and Thornes, 1979) could vary considerably from fan to fan.

What can be argued is that climatic change may involve changes in storm magnitude and frequency, causing changes in runoff rates, therefore in stream power. It may also involve changes in erosion rates from the mountain catchments, therefore sediment supply to the fan environment. Such changes could be further complicated by the presence of short-term intrinsic thresholds related to erosion of, or deposition on, the fan itself (Schumm, 1979).

Two approaches might give some indication of potential response to climatic change: (i) evidence at a regional scale from past, Quaternary, climatic changes; and (ii) topographic characteristics influencing patterns of aggradation and dissection at a local scale. The available evidence suggests (Harvey, 1978, 1984a, 1990) that major periods of fan aggradation coincided with Quaternary cold phases, and dissection with periods of lower sediment supply during warmer phases. There is a growing body of opinion that the Quaternary cold phases in this part of the Mediterranean basin were too dry to support woodland vegetation, and the warmer phases were sufficiently humid to support a tree cover (Butzer, 1964; Fairbridge, 1970; Amor and Florschutz, 1964; Sabelberg, 1977; Rohdenberg and Sabelberg, 1980). The present vegetation has been much modified by human activity, both within the mountain catchments and on the fans themselves, but locally trees are present and clearly tree growth is possible, at least in the less arid parts of the region. In this sense Holocene conditions, with a warm climate but only a limited vegetation cover, are unlike any Pleistocene conditions. Present precipitation totals are generally less than 300 mm (Geiger, 1970) but higher in the mountain source areas. The most important climatic parameter is the effectiveness of storm rainfall, in that it influences the generation of sediment and runoff on the mountain catchment, and the stream power through the fan environment, but it is a parameter about which we know little in relation to previous climatic conditions, and one that is beyond the usual scope of climatic change models.

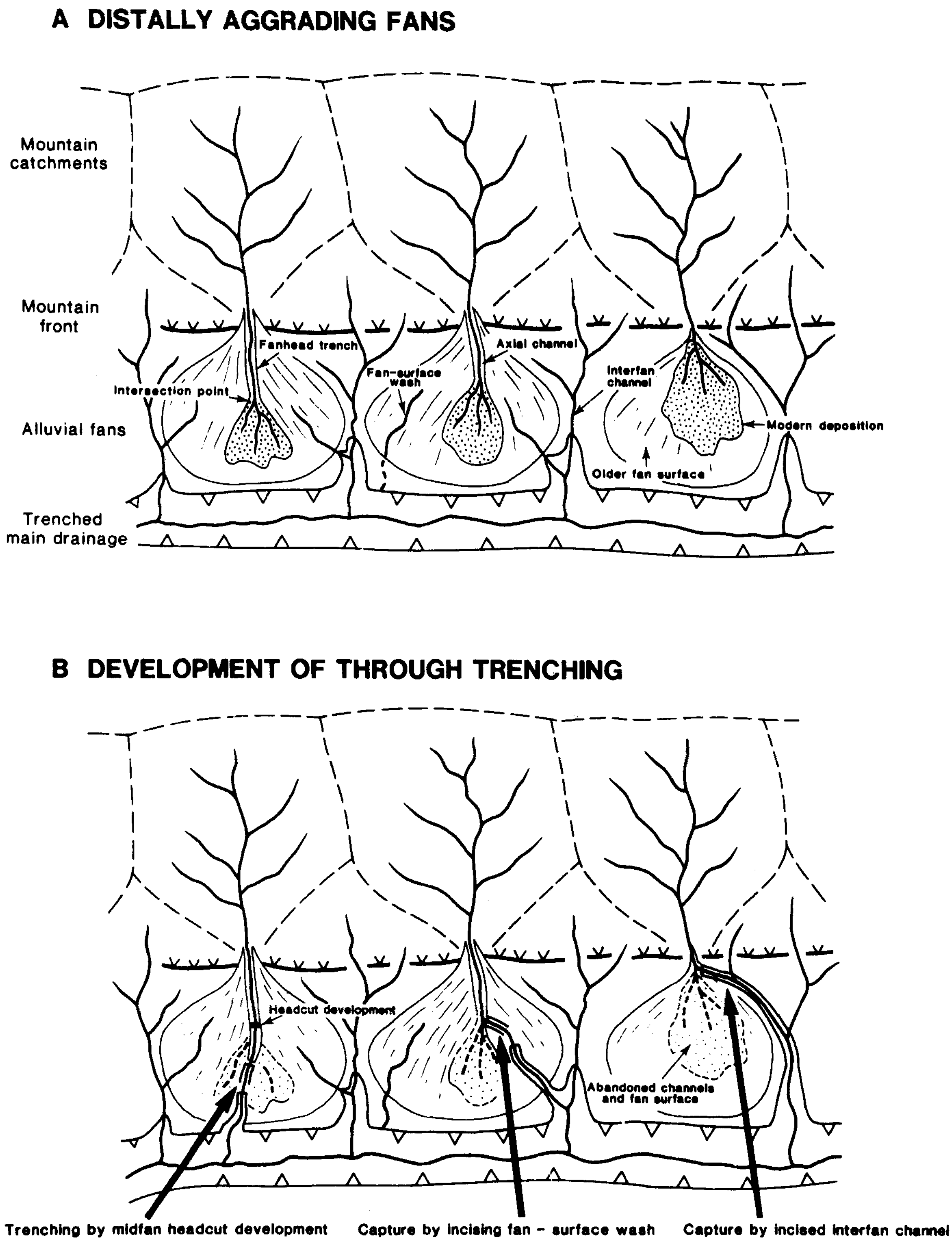

Figure 5. Schematic map of alluvial fan topography susceptible to trenching, by distal or interfan-induced dissection

Furthermore, as potential climatic change is unlikely to mirror Quaternary climatic changes, especially in the relationship between temperature, precipitation and changes in the effectiveness of storm rainfall, inferences from previous climatic conditions are not much help in predicting future fan response. This uncertainty is accentuated by the disparity between Pleistocene and Holocene climate/vegetation relationships. Future vegetation change, whether in response to climatic change or human activity, is unpredictable but could have a major influence on runoff and sediment generation.

More useful, perhaps, than inferences from the Quaternary would be an assessment at a local scale of the potential patterns of aggradation and dissection. If the response to future climatic change were to increase the supply of sediment to the fan environment, relative to stream power, we might expect fan aggradation to increase. On most fans this could involve an increase in the extent of the zones of contemporary sedimentation downfan from intersection points. On some fans, mid-fan headcut zones could become buried by sediment but in the absence of data on stream power it is difficult to suggest what types of change could occur on fans already trenched throughout their length.

If, on the other hand, the response were an increase in stream power relative to sediment supply, there would be an increased likelihood of mid-fan and distal trenching. This could be brought about by one of three possible mechanisms (Figure 5): (i) the conversion of profiles of types B or C to types D and E by the mechanism described by Harvey (1978); (ii) capture of the axial fan channel by an incising fan-surface wash; or (iii) capture in the fan apex area by a steep interfan channel. Fan zones that might be prone to these processes are indicated in the last column of Table I. Fans currently showing mid-fan scour or mid-fan headcut development could develop through fan-trenches by incision in mid-fan (M); those currently subjected to basal dissection (B) could become trenched throughout; and those fan zones adjacent to an incised main drainage, with steep interfan channels (I) could be vulnerable to the latter two mechanisms (ii) and (iii) outlined above.

Of the two trends, towards aggradation or towards dissection, the latter appears to be the most likely, if one of the features of any future climatic change were to be an increase in the effectiveness of storm rainfalls. The increased storminess of the period 1985–1990 in southeast Spain partly bears this out. The response of several fans to major floods in this period resembles that recorded on the Tabernas fans in 1980 (Harvey, 1984c). On the Nijar fans, Almeria, and the Carrascoy southern fans, major erosion occurred within the fan-head trenches, primarily of former fan or terrace deposits. Outside this study area, Cayola fan near Benidorm, Alicante (Harvey, 1978), now shows a 2 m deep trench within the fan-head trench, cutting into a formerly flat channel floor. However, in all these cases there is little evidence of much fresh sediment supplied to the fan from the mountain catchments, the major sediment sources to mid-fan and distal areas being older fan or channel deposits. Secondly, erosion is restricted to fan-head trench environments, the eroded sediment being redeposited further downfan, with no evidence for new incision in mid-fan or distal locations.

It is important to stress that alluvial fans represent only part of dry-region, mountain-fed fluvial systems. Their response to environmental change depends not only on runoff changes but also changes in the sediment system, on the coupling between mountain hillslopes and headwater channels, and the transport efficiency of the mountain channels in delivering sediment to the fan environment. Within the fan environment sediment sources include not only external sources from the mountain catchments, but also internal sources from older fan, terrace and channel deposits, and stream power depends not only on flood magnitude but also on channel geometry within the fan. Erosion within the fan environment may supply sediment from proximal to distal locations. However, if there are changes between aggradation and dissection in distal fan environments there are downstream implications for the major river systems. The buffering effect of the alluvial fan environment on the dry-region fluvial system as a whole may be radically changed, allowing the throughput of coarse sediment from the mountain source areas to the main stream system.

We know little of the thresholds controlling these processes in Spanish systems, nor do we know much of response times in these environments. If we are to increase our understanding of the role of dry-region alluvial fans, especially in the context of the fluvial systems of southeast Spain, in ways that will enable us to predict their response to future climatic change, long-term monitoring of sediment movement from hillslope to headwater channels to and through the fan environment should be undertaken for representative aggrading and trenched fans.

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